On the balance of the solar p–p chain

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Abstract

I show that the solar neutrino fluxes, predicted by standard nuclear and solar physics, can get closer to the experimental observations if one takes the freedom to introduce two free parameters into the model, as it is done in the MSW solution. I point out that the plasma electron capture of ^{7}Be and the ^{3}He(^{3}He,2p)^{4}He nuclear reactions deserve further experimental and theoretical attention.

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All four currently operating solar neutrino experiments, Homestake, Kamiokande, SAGE, and GALLEX, show a deficit of the solar neutrinos reaching the earth [1]. As these detectors have different energy thresholds, they are sensitive to different parts of the neutrino spectra. Table I shows the observed neutrino capture rates of the Homestake and gallium detectors compared with the predictions of Bahcall [2]. The ratio of the measured Kamiokande ^{8}B neutrino flux to the prediction of Ref. [2] is 0.51±0.04±0.06. We can see that the degree of deficit is rather different in the different type of experiments. Model independent analyses, which use only the luminosity constraint, have shown the following [3].

(i) The results of the three different types of experiments are hardly compatible with each other within the standard nuclear-, solar-, and neutrino model. If we take the ^{7}Be (ϕ_7), and ^{8}B (ϕ_8) neutrino fluxes as free parameters, then the best (but still not very good) fit to the three data would give a 50% reduction in the ϕ_8 flux, and a practically zero ϕ_7 flux [4]. The major contradiction seems to be between the Homestake and Kamiokande results. The deficit is much more severe in the former experiment, despite the fact that this experiment has contributions from neutrinos other than ^{8}B.

(ii) The ^{8}B neutrinos alone cannot be responsible for the solar neutrino deficit. This is because the gallium experiments are hardly sensitive to ϕ_8. It turns out that to get closer to the experiments, both ϕ_7 and ϕ_8 should be suppressed, but this suppression is much stronger in ϕ_7. It excludes the possibility that the inaccurate $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ cross section is the major source of the problem. In fact, the recently suggested low values of this cross section [5] would increase the theoretical ϕ_7/ϕ_8 ratio, thus even exaggregating the solar neutrino problem.

Currently, the favorite explanation of the solar neutrino problem is the Mikheyev–Smirnov–Wolfenstein (MSW) effect [6]. It assumes that the weakly interacting neutrino eigenstates (ν_e, ν_μ, ν_τ), which are linear combinations of the mass eigenstates, can transform into each other while interacting with the solar matter. In the two-component oscillation model the ν_e neutrinos are converted into ν_μ or ν_τ with the mixing angle θ and mass difference Δm. It can be shown that for certain values of θ and Δm the theoretical neutrino flux predictions of Table I can be reduced to the experimental values in all experiments, simultaneously, see, e.g., Ref. [7].

I would like to emphasize, however, that although the MSW mechanism is an exciting possibility, if we forget about its mathematical and particle physics pedigree, it is nothing but introducing two free parameters to fit three data. Moreover, these free parameters are introduced in a clever way, as they do not have any feedback on the energy generation of the Sun, thus θ and Δm can be chosen without any constraint. Also, there are reserves in this mechanism. If one wants to describe further neutrino experiments (e.g. atmospheric-, reactor-, etc. experiments) and the above scheme does not work, one still can introduce the third neutrino flavor, with the additional mixing angles and mass differences as free parameters. However, as the number of independent data is larger and larger, we are running out of free parameters, and have to introduce other exotics, such as sterile neutrinos, inverted mass hierarchy, etc. [8].

If we allow ourselves to introduce two free parameters into the model, we can do it in a simpler way, without introducing a new mechanism, beyond the Standard Model. We can keep the standard nuclear-, solar-, and neutrino physics, and introduce these parameters into such nuclear reactions, whose cross sections have never been measured in the interesting

energy range. I emphasize, that the following is currently only a pure theoretical possibility, without any supporting experimental evidence or theoretical reaction model. But currently the same is true for the MSW mechanism.

A careful survey of the $p-p$ chain suggests, that the best places to introduce free parameters are the ^{7}Be(e^-,ν)^{7}Li electron capture from the solar plasma, and the ^{3}He(^{3}He,2p)^{4}He reaction. The capture rate of the ^{7}Be(e^-,ν)^{7}Li reaction is thought to be known with high precision because its knowledge requires only "weak interaction theory and the local physical condition of the solar plasma" [2]. Let me point out, however, that there are cases where only standard atomic physics takes places, and still there are factor of two differences between theory and experiment. Such a case is, for example, the electron screening in low-energy nuclear reactions [9]. Without any experiment, we cannot be *a priori* sure that the ^{7}Be(e^-,ν)^{7}Li capture rate is correct. If this rate were smaller than the current theoretical value by a factor of two, then it would decrease the ϕ_7 flux and increase the ϕ_8 flux by the same amount.

It was suggested twenty years ago, that a low-energy resonance in the ^{3}He(^{3}He,2p)^{4}He reaction would suppress both the ϕ_7 and ϕ_8 neutrino fluxes [10]. The latest experiment went down to 25 keV energy without observing a resonance [11]. The LUNA experiment, currently running at Gran Sasso Laboratory, is planning to reach 15 keV [12]. At such low energies, deep below the Coulomb barrier, the properties of such a hypothetical resonance are solely determined by the Coulomb penetration. It can be seen, that such a resonance, if existed somewhere betwen 15 keV and *zero* energy, would cause the suppression of the ϕ_7 and ϕ_8 fluxes by a factor of 4.3 and 3.3, respectively [13]. (This is in the case of a 0^+ resonance; other resonant partial waves could cause even higher suppression.) It means, that even if the experiments could reach 10 keV by heroic efforts, the existence of a state, which would have strong influence on the neutrino fluxes, is still possible below this energy.

The combined effect of the above-mentioned two changes in the cross sections would be a reduction of ϕ_7 by a factor of 8.6 and that of ϕ_8 by a factor of 1.6. Although the agreement with the solar neutrino experiments would not be perfect, all theoretical predictions would move toward the right direction, and the ϕ_7/ϕ_8 ratio would considerably decrease. I note, that these changes of the neutrino fluxes are only first order estimates, because they neglect the feedback to other reactions of the $p-p$ chain. The correct way to calculate the effects of the changes of the nuclear cross sections would be to use these cross sections in a solar model. Such a study is in progress.

In conclusion, I have emphasized, that from practical point of view, currently the MSW solution of the solar neutrino problem is nothing, but introducing two free parameters to fit three data. If we allow ourselves this amount of freedom within the nuclear physics part of the problem, we could also get considerably closer to the experimental results, without going beyond the Standard Model. The most interesting reactions of the solar $p-p$ chain, from this point of view, are the ^{7}Be(e^-,ν)^{7}Li electron capture from the solar plasma, and the ^{3}He(^{3}He,2p)^{4}He process. These reactions should deserve further theoretical and exprimental studies. My preliminary theoretical studies of the ^{3}He(^{3}He,2p)^{4}He reaction show, for example, that the dynamics of this process is much more complex than the existing models have assumed so far, and involves dynamical degrees of freedom of the six-nucleon problem, that were not included before [14].

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TABLES

TABLE I. Neutrino capture rates in the Homestake and gallium experiments.

Neutrino source	Capture rate (SNU)	
	Homestake	GALLEX & SAGE
pp	0.0	70.8
pep	0.2	3.0
hep	0.03	0.06
^{7}Be	1.1	34.3
^{8}B	6.1	14.0
^{13}N	0.1	3.8
^{15}O	0.3	6.1
^{17}F	0.003	0.06
Total	7.9 ± 0.87	$132^{+6.7}_{-5.7}$
Experiment	2.55 ± 0.25	$79 \pm 10 \pm 6$ $\quad 74^{+13+5}_{-12-7}$